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A New Approach for Routing Plane Construction in Future Multi-Plane Routing based Wireless IP Access Networks

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***Abstract*—There has been a rapid rise in the IP traffic throughout the Internet which takes advantage of the already established widespread IP infrastructure. Different suggestions are being explored to facilitate the next-generation access networks via IP mechanisms, with a growing trend towards a flat-IP structure and novel topological set-ups in the backhaul. Aligned with this evolution, there are increasingly more user applications flooding the Internet that calls for a consistent routing strategy to minimize loss in data transmission. In this paper, Multi-Plane Routing (MPR), which incorporates various aspects in all-IP infrastructure will be studied under the new access network structure. MPR is based on Multi-Topology Open Shortest Path First (MT-OSPF) principle and divides the physical network topology into several logical Routing Planes (RPs). The offline Traffic Engineering (TE) strategy for MPR has been optimized using a heuristic hop-constraint solution that suits the "flattened" network realized through the incorporation of direct communication between Aggregation Routers. With our approach, despite of a higher number of $Ingress-Egress$ pairs for traffic in the access network, the number of RPs has been kept to the desirable level whilst the reliability indicator and the path diversity index ratio have increased up to 47$\%$ and 33$\%$ respectively. Our proposed MPR-based offline approach has also shown improvement compared with the Multi-Protocol Label Switching (MPLS) offline approach.**

I. Introduction

The exponential growth of Internet has turned it into a multi-faceted collaborative environment connecting a wide range of users. The emergence of exciting new devices along with new highly demanding applications have put even more burden on the Internet. Today, Internet is still best-effort, this means that with the advent of high speed links, IP Network Providers (INPs) have increasingly adopted bandwidth over-provisioning strategy [1]. It is essential for the INPs to apply Traffic Engineering (TE) in order to deal with both inter- and intra-domain traffic, aimed at improving the network's performance. IP is now the dominant internetworking protocol and with the rapid rise in the IP-based applications combined with faster radio access technologies throughout the Internet; cellular wired backhaul and Internet access based network designs are converging on the IP-based infrastructure model. Currently, most access networks use Multi-Protocol Label Switching (MPLS) [2] which delivers services over a dedicated single infrastructure through creating Labelled Switched Paths (LSPs). In MPLS, the scalability and robustness become an issue due to the complexity and overhead associated with building and maintaining LSPs to which flows are mapped. Open Shortest Path First (OSPF) is a commonly used intra-domain dynamic link-state IP protocol. OSPF is scalable and robust against element failures but does not support arbitrary traffic splitting as opposed to MPLS. Equal-Cost Multi-Path (ECMP) is an add-on option of OSPF [3] that allows the equal splitting of traffic which is not sufficient for near-optimal performance as compared to MPLS. ECMP is highly intractable in case of diverse and random topologies for numerous cases of sources and destinations.

A. Related Work and Background

In order to address the deficiencies of OSPF in terms of utilizing multiple routes, MT-OSPF has been proposed [4] which suits the all-IP network infrastructure, improves load balancing and avoids problems associated with MPLS and ECMP [5]. Also, Wang. et al. [6] claimed that by partitioning the overall network demand into multiple subsets at the edge of the network, near-optimal performance could be achieved. Multi-topology routing has initially been introduced for core and transit networks. The structure of IP access networks demands new considerations in IP-routing primarily due to tree-like topologies. Access networks generally consist of a transit routing space that connects the access nodes to the core network through gateway. Traffic flows between gateway and access nodes in both directions, and between access nodes. In accordance, path diversity in access networks is increasingly being considered. The potential gain offered by path diversity in access networks was investigated in [7]. This study substantiated the need for next generation access networks' evolvement to more meshed topologies in order to exploit path diversity materialized by multi-path routing. MPR is a MT-OSPF based approach which incorporates various aspects in the all-IP infrastructure and applies an IP-based TE approach based on maximizing path diversity facilitated by multiple logical RPs of OSPF routing. MT-OSPF was originally laid out for fast re-route in case of node/link failure whereas MPR employs MT-OSPF for load balancing. MPR is designed to improve network's performance through the application of an offline TE method in order to build RPs ahead of the traffic flow in the network which follows an online TE approach [8,9]. MPR is envisioned to be configured using the IP-header integrated ToS/DiffServ's unused bits (i.e.

3 precedences). A reference scenario was applied showing how MPR outperforms OSPF in terms of different network metrics [8]. The case where there exists dedicated paths for every $Gateway$ (GW)-$Aggregation\ Router$ (AR) pair was previously studied. Under this scenario, the traffic destined for outside of the network towards the big Internet and the internal traffic between the ARs would pass through the gateway. This structure is restricted to 3G environment's architectural functionality where the entire traffic travels through the core. We are targeting to expand our model to converge the Internet routing and future cellular systems' requirements by modifying the RP structure, allowing for direct communication between the ARs.

B. Outline and Contributions

In this paper, we propose a new TE mechanism aligned with the changing access network structure based on the MPR scheme. To this end, we extend the research conducted in [8] and [9] by building direct communication paths between the ARs in our reference topologies (as normally envisaged in OSPF implementations) achieved through the modification of the RP structure and based on the newly proposed RP construction methods. This was materialized through the extension and enhancement of the offline algorithm. In addition to topologies with ARs strictly positioned at the edge, new topologies are added to our study with ARs spread out in the transit space. In this work, we focus on the offline TE aspect (network planning phase) of MPR which has the physical topology with associated link capacities as the input. Under the new scenario, the topology independent RP construction is optimized through the introduction of new properties to the RP construction algorithm. Our design concept is equally reflected in the trends towards a flat-IP structure in cellular networks [10,11]. Hence, base stations are directly interconnected by IP and the forwarding domain barriers in these networks (i.e. radio access and core networks) are being abolished making the new backhaul connection space open to diversification of paths via meshed hierarchical topological set-ups. In fact, with the expected increase in the backhaul traffic, wired backhaul links' overload could be alleviated by the diversity offered by MPR. Since we add AR-AR routes under the new scenario, each plane would end up with a larger number of paths than in the initially investigated scenario, hence the overall hop-count and utilization of the topology in each plane become important metrics. In earlier studies for MT-OSPF [6], it was concluded that overall near-optimal network performance in terms of cost and link utilization can be achieved with up to 3-5 RPs as also substantiated in [8] for MPR. Lower number of RPs would also ensure minimum implementation and routing table maintenance overhead. In order to obtain the desired number of planes aimed at the improvement in the QoS performance as concluded in [12], hop-constraint was introduced. It was shown that despite hop-constraint's application led to higher path costs, it improved the QoS and service delivery for the various tested network designs. Hop-constraint can be associated with lower delays. The traversal of many links during transmission leads to higher overall delays [13]. Hop-constraint is also aligned with reliability defined as the probability of the session for every $Ingress - Egress$ pair not being interrupted by any external factors such as link failure [14]. Lower reliability can have a negative impact on service delivery and QoS performance [15]. RP construction considering the aforementioned metrics is investigated through the introduction of the Quality of Plane-set (QoP) which provides an analytical overview of the constructed RPs' configuration efficiency. We will also show the superiority of our MPR-based approach over the MPLS offline approach.

The contributions of this paper are threefold. First, we propose three novel heuristic RP construction methods based on which the extent of building paths in each logical topology is investigated by adding direct paths between ARs to accommodate the changing structure of access networks. Second, hop-count was introduced as a constraint in each RP which is used as an investigation parameter for finding the optimal configuration based on the number of RPs in physical topologies. Third, we proposed a method for assessing the quality of logical topologies.

II. OFFLINE ALGORITHM FOR BUILDING RPS

A. Concept

MPR divides the network into multiple logical planes. This allows the routers in one OSPF area to maintain several independent logical planes. Each RP is an instance of OSPF associated with a dedicated link weight configuration and it can overlap with another or share any subset of the underlying network. Each router maintains different routing information bases and forwarding information bases through which routes between ARs and the gateway are defined in every plane. Each RIB/FIB represents one RP.

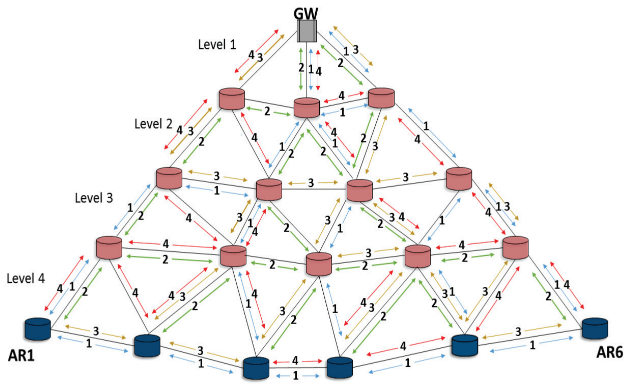


Fig. 1: Sub-topology (T1M5, see TABLE I) of the 19 node based network. 4 RPs are demonstrated.

B. Simulation Setup

The network in Fig. 1 represents an autonomous system which can be a campus or metropolitan access network with a single gateway towards the big Internet. This reference fat-tree model is based on [16]. Nodes are considered to be

Topo	Nodes	ARs	Links	Avg. Node degree	Total capacity (Gb)
T1M1	19	6	18	1.9	7.84
T1M2	19	6	32	3.36	11.94
T1M3	19	6	36	3.79	12.98
T1M4	19	6	39	4.1	14.06
T1M5	19	6	41	4.32	15.34
T2M1	32	14	31	1.94	9.84
T2M2	32	14	53	3.31	15.28
T2M3	32	14	59	3.7	16.48
T2M4	32	14	61	3.82	16.88
T2M5	32	14	65	4.06	18.00
T2M6	32	14	67	4.19	18.40

TABLE I: Setup of the topologies

interconnected by wired Ethernet links. The network is comprised of 6 base stations acting as Aggregation Routers. Link capacities are set up depending on the level they belong to as demonstrated in the reference network. 34, 27, 20 and 10 Mbps (values used for normalization) are used for four different levels respectively in the first network studied (19 nodes). 34, 27, 20, 15 and 10 Mbps are used for five different levels respectively in the second network studied (32 nodes) with 14 base stations. It should be noted that the network portrayed is the base topology to which a different meshing degree (node degree) is applied to create several sub-topologies. The RPs are built considering that traffic can exist internally between the ARs and towards the Internet through the gateway. TABLE I presents the specifications of the eleven topologies investigated to provide diversified network scenarios for demonstrating the concepts of MPR. x indicates the topology number and y denotes the meshing configuration in every topology $TxMy$. $T1M1$ and $T2M1$, which are sub-topologies for the network 1 and network 2 respectively, represent strict trees. $T2My$ topologies include added ARs spread out in the transit space which set it apart from the previously studied scenario with ARs strictly located at the edge, i.e. $T1My$ topologies.

C. Graph Theoretical Representation

Topology of a given communication access network is represented by a connected directed graph $G = (\mathcal{V}, \mathcal{E})$. The network is comprised of a set $\mathcal{E}$ of E ($\mathcal{E} : e = 1, ..., E$) edges with finite capacities C_e and a set $\mathcal{V}$ of V ($\mathcal{V} : v = 1, ..., V$) vertices. Let $\mathcal{K} : k = 1, ..., K$ symbolize the number of ARs in the network. The set of Routing Planes (RPs) is represented as $\mathcal{N} : n = 1, ..., N$. Every $e \in \mathcal{E}$ is assigned with $|N|$ distinct link weights denoted by $(w(n, e), n \in \mathcal{N})$. The network supports a set of demands for every $Ingress - Egress$ pair denoted by $\mathcal{D}$ of $D(\mathcal{D} : d = 1, ..., D)$. The egress nodes are $Egress : \{GW \;\&\; \{AR_k\}_{k=1}^{K} \backslash \{AR_{\mathcal{S}}\}_{\mathcal{S}=1}^{S}\}$. Let f symbolize the number of destination nodes. Let $AR_{\mathcal{S}}$ ($\in AR_k$) be the source AR ($\mathcal{S} = 1, 2, .., S$). AR_{fi} ($\in AR_k$) represents the first destination AR while AR_{la} ($\in AR_k$) represents the last destination AR on the network in one iteration before the source AR ($AR_{\mathcal{S}}$) changes for the next iteration until all the ARs are covered. The connections are duplex therefore, all the destinations can be sources as reflected in the overlapping RPs built for all the ARs and GW. Every RP is comprised of $\rho_n^{\mathcal{K}} : \rho_n^k = \rho_n^1, \rho_n^2, ..., \rho_n^K, \rho_n^{K+1}$ set of shortest paths. $\rho_n^{\mathcal{K}}$ incorporates the demand-set $\mathcal{D}$ for $P_n^{d=1}, ..., P_n^{d=D}$ in routing plane n for all the ARs and GW. Therefore there are $P_n^{d=D} \subset \rho_n^{\mathcal{K}}$ acyclic shortest paths for demand d and RP n according to the link weight configuration W_n for that RP. The position of every link in path P_n^d is represented by a set $\mathcal{H}$ of $H(\mathcal{H} : h = 1, ..., H)$ hops. The set of path sets $(\rho_n^1, \rho_n^2, ..., \rho_n^K, \rho_n^{K+1})$ for all the ARs and GW represent one RP.

$$\rho_n^k = \begin{bmatrix} AR_{\mathcal{S}} & . & . & . & GW & : P_n^{d_k=1} \\ AR_{\mathcal{S}} & . & . & . & AR_{fi} \neq AR_{\mathcal{S}} & : P_n^{d_k=2} \\ \vdots & & & & & \\ AR_{\mathcal{S}} & . & . & . & AR_{la} \neq AR_{\mathcal{S}} & : P_n^{d_k=f} \end{bmatrix} \quad (1)$$

The AR-GW pair is reserved in every RP for the case that the network id of the desired address is located outside of the network and vice versa. $d = 1$ represents the AR1-GW pair in path-set ρ_n^1 and the demand increments up to D corresponding to the final pair in path-set ρ_n^{K+1}.

An $N \times E$ matrix R^d represents the link usage. $R^d_{eP_n^d} = 1$ if path P_n of pair d uses link e and $R^d_{eP_n^d} = 0$ otherwise. Path Diversity Index (PDI) as originally presented in [8] represents the number of RPs that include e in their shortest path for demand d:

$$PDI_e^d = \sum_{n \in \mathcal{N}} R^d_{eP_n^d} \quad \forall e \in \mathcal{E} \;\; and \;\; \forall d \in \mathcal{D} \quad (2)$$

The ultimate objective is to minimize the chance that for a given demand all RPs share a single link; secondly to maximize the chance that any link is used in at least one RP. Full Path Diversity Index (FPDI) is introduced in [8] which designates whether a critical link e is included in shortest path for pair d in all RPs. FPDI is equal to 1 if $PDI_e^d = \mid N - 1 \mid$ and 0 otherwise. The link weight assignment is described as follows: to calculate $\mid N \mid$ set of positive link weights $W_n = w(n, e) : 1 \preceq w(n, e) \preceq L$, with $\forall n \in \mathcal{N}, \forall e \in \mathcal{E}$ and $L (= 2^{16} - 1)$ as the highest value that OSPF can handle in order to maximize:

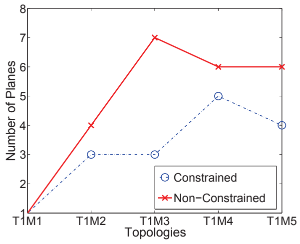
$$\sum_{d \in \mathcal{D}} \sum_{e \in \mathcal{E}} FPDI_e^d \quad (3)$$

$\bar{d}_s$ is represented as the average length of the shortest path in terms of hop-count from any source u to all the destinations v across the available planes under a given topology. $d_n^k(u, v)$ is the length of the shortest path from node $u \in Ingress$ to $v \in Egress$ in every path-set ρ_n^k.

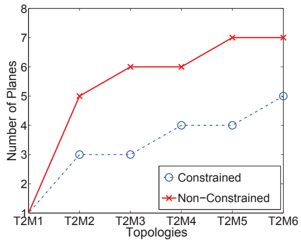
$$|\bar{d}_s| = \frac{1}{N} \left(\sum_{n=1}^{N} \sum_{k=1}^{K+1} (| \frac{1}{|V| - 1} \sum_{(u,v) \epsilon V, v \neq u} d_n^k(u, v)|) \right) \quad (4)$$

D. RP Construction

The pseudo-code of the algorithm is presented as **Algorithm 1**. Initially, Cisco's InvCap is applied in assigning weights to the links. i.e. for each link $e \in E$, $w(1, e) = 1/C_e$. After building the first RP, three heuristic methods are used for computing the link weights. 1) Iterative Plane Construction, 2) Link Degree of Involvement, 3) Maximum link degree



(a) Number of planes for the 1st set of topologies



(b) Number of planes for the 2nd set of topologies

Fig. 2: Number of planes with and without hop-constraint, $X = 64$

involvement per demand. The link weight configuration for these methods is obtained as follows:

$$w(n,e) = \frac{\max_{e\in\mathcal{E}}(C_e)}{C_e} + \frac{1}{N}\sum_{n=1}^{N-1} w(n,e) + \alpha_e(n)/\beta_e(n)/\gamma_e(n)\cdot X \tag{5}$$

with $\forall e \in \mathcal{E}, \forall n \in [1, N-1]$ and with the following :

$$\alpha_e(n) = \begin{cases} 1, \text{ if link } e \text{ is in a path in RP } n-1 \text{ ;} \\ 0,\text{otherwise} \end{cases} \tag{6}$$

$$\beta_e(n) = \sum_{n=1}^{N-1} \alpha_e(n),\ \ \gamma_e(n) = \max_{d\in\mathcal{D}}\left(\sum_{n=1}^{N-1}\alpha_e^d(n)\right) \tag{7}$$

$\alpha_e(n), \beta_e(n), \gamma_e(n)$ represent method 1, method 2 and method 3 respectively. X is a multiplicative parameter that is used for the granularity of the methods. The higher the value of X, the more RPs will be tested. X ranges from 1 to X_{max} incremented by 1 with $X_{max} = \{2; 4; 8; 16; 32; 64\}$. Method 1 only considers the involvement of a link in RP in $N-1$. Method 2 considers the involvement of a link e in all RP $n \in [1, N-1]$. Method 3 is in fact a subset of method 2 where the cost of the most used link e in RP is penalized. Subsequently, correlation between the three contending planes resulting from the aforementioned methods is calculated against the fixed physical topology. The mean correlation is obtained for the resulting RPs from the $(1 : X_{max})$ loop and the plane with the lowest correlation is picked, on which the Djisktra's algorithm is performed. There is a set of rules which should be met in the RP construction algorithm: 1) Each link must not be utilized in at least one plane. This is to ensure that PDI_e^d does not reach beyond its maximum ($| N-1 |$) per link. 2) There exits a route for every demand. Routers in between can be either sources or sinks. 3) Each link is used in at least one plane in order to ensure path diversity.

III. Plane-set Selection Criteria

A. *Hop-Constraint Optimization*

When applying MPR's off-line algorithm to build RPs connecting the AR-AR and AR-GW pairs, the resultant paths would render long routes between the ARs in terms of hop-count. Some of these routes would pass through the gateway or through nodes located very high in the distribution layer. This would not be desirable in our study to apply the MPR technique under the new scenario where access points communicate directly. The long routes between ARs contribute to a higher number of RPs constructed per topology as there will exist more redundant paths available per plane. That's why we use hop-constraint to select an optimal set of RPs. Hop-constraint optimization was originally introduced in [17]. Here, we have added more constraints and have reformulated certain representations in order to adjust the optimization problem to our work. Weight of link e between any two nodes (i, j) for demand d in plane n is denoted by $w_{ij}^d(n, e)$. The decision variables are defined as followed: $R_{(ij)P_n^d}^d$ is equivalent to equation (1) and is defined as the binary directed variable which indicates whether $arc(i, j)$ is in the minimal spanning tree and $Z_{(ijb)P_n^d}^d$ is the directed binary flow variable that indicates whether $arc(i, j)$ is included in the only path from the source to the destination node b $\in Destinations : \{GW; AR_k \neq AR_S\}$ at position h in RP n.

$$Z_{(ijb)P_n^d}^d = \begin{cases} 1, \text{ if arc}(i,j) \text{ is in the path from root node t} \\ \quad \text{to node } b, b \neq i \\ 0, otherwise \end{cases} \tag{8}$$

We are minimizing the number of hops across a set of RPs

Algorithm 1: Offline Algorithm for Building RPs

1: **procedure** RP-CONSTRUCTION
2: Build InvCap Link Weight Matrix
3: **if** rules (1 & 2 & 3) are respected: jump to step 8
  else: go to step 4
  end if
4: **for** $X = 1 : X_{max}$
   Construct RPs using Method 1, Method 2, Method 3
  end for
5: Find the best plane resulted, through correlation
6: Compute Dijkstra on the resultant plane
7: Go back to step 3 (the verification process)
8: Application of hop-constraint, minimizing $|\bar{d_s}|$
a) Check the hop number for all the routes $(P_n^{d=1}, ..., P_n^{d=D})$ in every plane
  if there exits a corresponding arc(i,j) in position h:
   Discard the corresponding planes for that hop number h
  end if
b) Test the output to ensure the constraints' criteria (equation 11) are met
  if the constraints' criteria are met:
   Pick a hop-constraint value: Algorithm terminated, go to step 9
  else:
   Hop-count is incremented: go back to step 8
  end if
9: RPs are obtained for AR-AR and AR-GW pairs
10: **end procedure**

obtained under a given topology. ($\forall e \in \mathcal{E}$ & $\forall d \in \mathcal{D}$)

$$\min \sum_{n=1}^{N} \sum_{(i,j)\epsilon V} w_{ij}^{d}(n,e).R_{(ij)P_n^d}^{d} \tag{9}$$

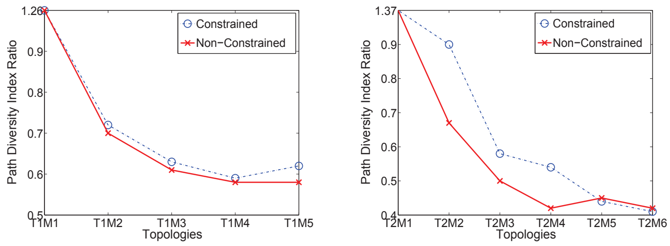
s.t.

$$\begin{cases} 2 < N < 6 \qquad \forall Topolgies \neq \text{T1M1,T2M1} & (1) \\ \sum_{(i)\epsilon V} R_{(ij)P_n^d}^{d} = 1 \qquad \forall j\epsilon V \neq AR_{\mathcal{S}} & (2) \\ \sum_{(i)\epsilon V} Z_{(ijb)P_n^d}^{d} - \sum_{(i)\epsilon V \neq t} Z_{(ijb)P_n^d}^{d} = 0, & \\ \qquad \forall b, j\epsilon V \neq AR_{\mathcal{S}}, j \neq b & (3) \\ \sum_{(i)\epsilon V} Z_{(ijj)P_n^d}^{d} = 1 \qquad \forall j\epsilon V \neq AR_{\mathcal{S}} & (4) \\ \sum_{n=1}^{N} \sum_{(i,j)\epsilon E} Z_{(ijb)P_n^d}^{d} \leq H.D.N \quad \forall b\epsilon V \neq AR_{\mathcal{S}} & (5) \\ Z_{(ijb)P_n^d}^{d} \leq R_{(ij)P_n^d}^{d} \qquad \forall (i,j)\epsilon E, b\epsilon V \neq AR_{\mathcal{S}} & (6) \end{cases} \tag{10}$$

As a result of this optimization, every plane-set would become constrained by a hop number denoted by H. Constraint (1) represents the plane-constraint for all the topologies except for $T1M1$ and $T2M1$ which are strict trees. This means that only one plane is achieved under these two topologies. It is assumed that with higher number of planes and accordingly a higher number of paths, traffic can be better balanced. As stated earlier in section I-B and shown in [6] and [8], this assumption is wrong and 3-5 planes would be sufficient in achieving near-optimal performance. We considered a smaller upper bound (< 4) for $T1M2$ and $T2M2$ as a lower number of RPs with long redundant routes result due to lower meshing. Constraint (2) ensures that every node in the path is in the solution and has only one arc entering it. Constraint (3) states that only one arc enters a node in position h in any path and there is only one arc leaving that node in position $h+1$. Constraints (4) and (5) ensure that only one arc in position h enters the destination node for every demand in every path-set ρ_n^k. These two constraints guarantee the feasibility of the solution. Constraint (6) states that if $arc(i,j)$ is included in the solution, it exists in the path between the source and its corresponding destination node. Fig. 2 demonstrates the decline in the number of planes to the desired range post hop-constraint. In our study, $X = 64$ results in the best set of RPs obtained under the tested topologies.

B. Quality of Plane-set (QoP)

QoP determines the quality of every set of RPs post construction based on some generic parameters. QoP also provides a comparative analysis in order to determine whether the hop-constraint which was introduced to select the optimal number of planes, improves the quality of the RPs. We also compare our MPR based methods with the MPLS offline TE approach. In the latter case, the weight for every link was set to 1 and the same number of paths as the MPR constrained case were built for every demand simply by using hop-count increment to allow for the creation of Q multiple paths. This approach aims to mimic the MPLS offline TE approach where multiple LSPs are built for every demand with a hop-count threshold while ensuring one node-disjoint path (or atleast a maximum number of nodes being disjoint if not all)[1]. The number of LSPs are



(a) PDI Ratio for the 1st set of topologies

(b) PDI Ratio for the 2nd set of topologies

Fig. 3: Overall PDI Ratio for all the available links across a set of planes, $X = 64$

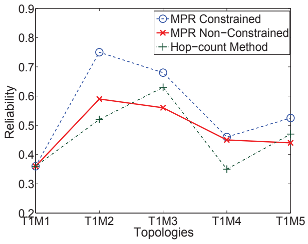
set based on a a set of given metrics as detailed in [1] (such as hop-threshold and a node-disjoint path) hence reducing the number of LSPs needed, obtaining as many as desired by the network planner. Accordingly, we set the metrics such that the same number of LSPs as the RPs in the MPR constrained case were obtained (i.e. equivalent to our optimum configuration). Henceforth for simplicity in formulation, N will also represent Q number of LSPs ($Q \equiv N$).

1) Path Diversity Index Ratio (PDI Ratio): We define PDI Ratio as PDI across a set of available RPs relative to the maximum possible PDI across a set of available RPs under a given topology (PDI was introduced in subsection II-C).

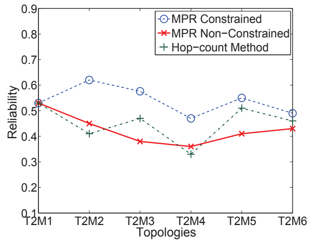
$$QoP \propto \frac{\sum_{d=1}^{D} \sum_{n=1}^{N} R_{eP_n^d}^{d}}{(\sum_{1}^{E} e).(|N-1|)} \tag{11}$$

PDI Ratio is indicative of how close to optimum (i.e. 1) our network is in terms of PDI. Fig. 3 shows that PDI is generally closer to optimum with a lower number of available RPs (as it is the case post-constraint) for most of the topologies. There is an exception in case of $T1M1$ and $T2M1$ (strict trees) where the PDI Ratio is higher than optimum as more links get over-utilized relative to the only available RP. We haven't included MPLS in Fig. 3 as the MPLS method does not consider path diversity in building multiple LSPs to obtain a balanced link usage distribution (no optimum to compare against). In fact; the absence of path diversity in the MPLS case leads to some links ending up not being used, putting a burden on other links. From a network planning perspective; as explicit routing (pre-defined routes for every demand) is applied in both MPR and MPLS, the imbalance of link usage in case of MPLS in the offline mode will lead to a higher maximum link utilization when traffic flows in the network with certain links getting congested quicker. The average maximum LSP occupation of a link was measured as $|1.07 \times N|$ and $|1.13 \times N|$ ($Q \equiv N$) throughout the first and second set of topologies respectively as opposed to $|N-1|$ in the MPR case for both cases.

2) Reliability: If failure is associated with some probability p, assuming failures are independent and equal for all the links, the probability of a path with h arcs being operational is given by $(1-p)^h$ [13]. The links would also get penalized if included in more than one plane or overlapping with more than one LSP path. Consequently, the overall reliability per demand across a set of available independent planes associated with QoP can

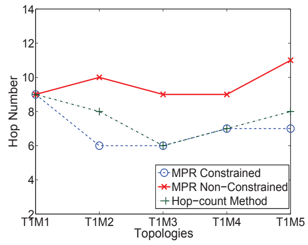


(a) Total per-demand reliability indicator for the 1st set of topologies

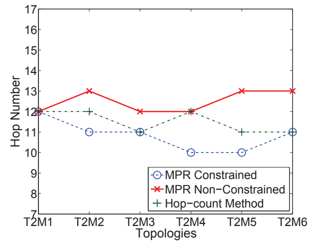


(b) Total per-demand reliability indicator for the 2nd set of topologies

Fig. 4: Overall per-demand reliability indicator obtained under randomly generated probabilities of failure p across the links, $X = 64$



(a) The maximum hop number for the 1st set of topologies



(b) The maximum hop number for the 2nd set of topologies

Fig. 5: The maximum hop number, $X = 64$

be derived as follows:

$$QoP \propto \sum_{d=1}^{D} \frac{1}{N} \left(\sum_{n=1}^{N} \prod_{h=1}^{H} (1-p)^{\sum_{n=1}^{N} R^{d}_{eP^{d}_{n}}} \right) \qquad (12)$$

It is easy to conclude that every individual path in one plane with a lower hop-count would have a higher reliability. Fig. 4 demonstrates the reliability indicator for all the demands across the total available RPs being higher post-constraint, which is due to shorter paths in terms of hop-count. The reliability in case of the MPLS method is consistently lower compared to the MPR constrained case (where the number of LSPs and RPs built are equivalent), mainly due to more links having been overused and hence penalized more throughout the constructed LSP paths. The results obtained in Fig. 4 are based on a set of distinct probabilities of failure being randomly distributed among the links.

3) Hop-count: As reflected in Fig. 5, the maximum hop-count per plane-set across all the demands would decline as a result of hop-constraint. It can be also observed that lower number of hops are transversed in the MPR constrained case compared to the MPLS case. The maximum hop-count represents the worst case of path length in a topology among the RPs. The maximum path length for the MPLS method is indicative of the maximum hops needed to build multiple LSP paths per demand.

$$QoP \propto \max_{d=1}^{D} \left(\max_{n=1}^{N} H \right) \qquad (13)$$

IV. Conclusion

In this paper, we have proposed an extended modified MPR-based TE approach in all-IP access networks. The trend towards a flat-IP structure reflected through the expected direct IP connectivity between the base stations demands a new routing mechanism. This mechanism allows the network to maintain several independent logical topologies which can be used to balance the traffic load in the network. Hop-constraint is introduced to select a set of RPs, resulting in an optimally configured network. QoP is proposed as an evaluation metric to gauge the quality of the RPs in terms of various metrics in the offline mode. With our approach, the number of RPs has been kept to the desirable level despite of having a higher number of $Source - Destination$ pairs. Moreover, the reliability indicator and the PDI Ratio have increased by 21% and 10% on average respectively. Our MPR-based approach has also shown enhancement over the MPLS approach. For future work, mobility and heterogeneity aligned with 5G concepts in MPR-based networks will be investigated.

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